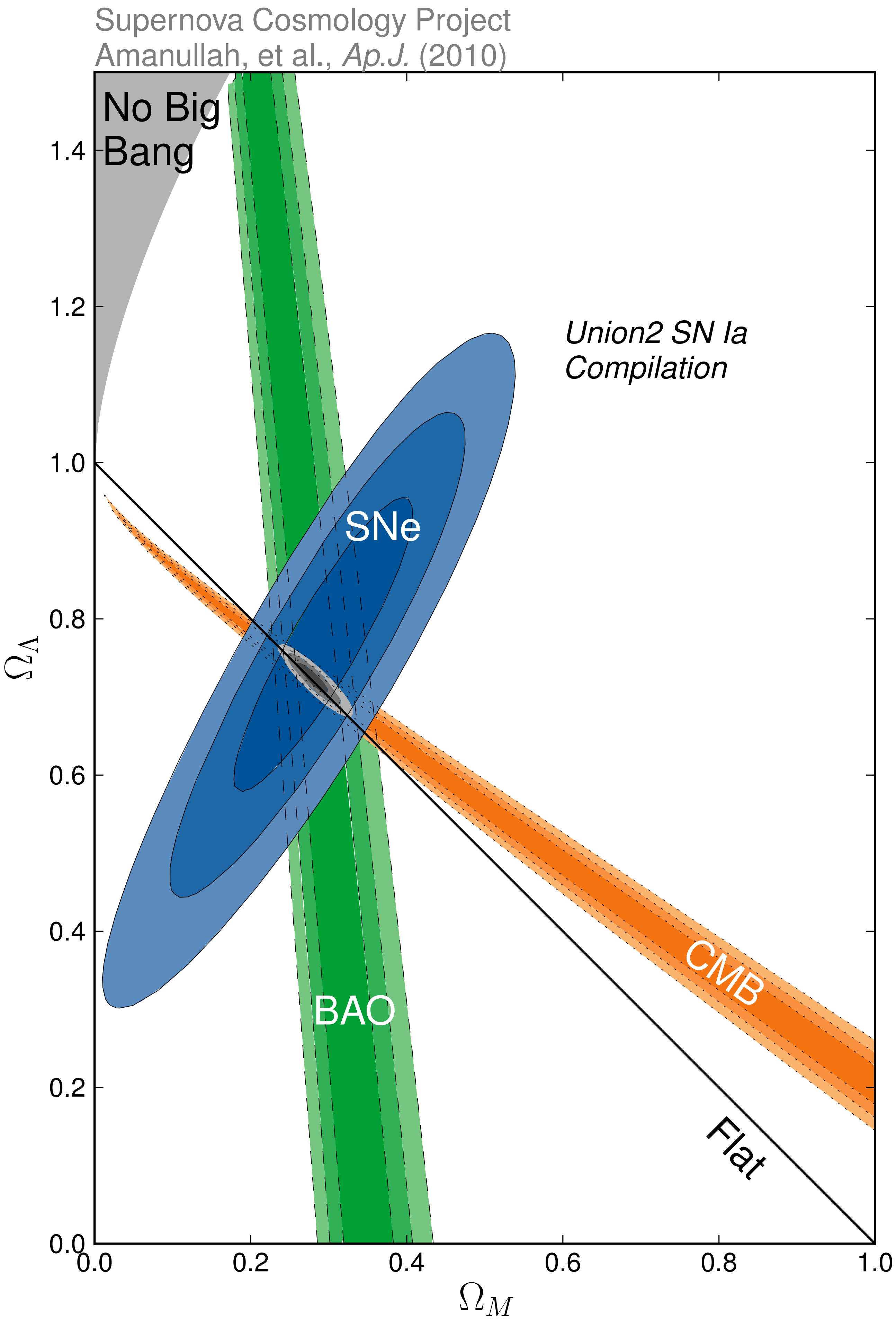
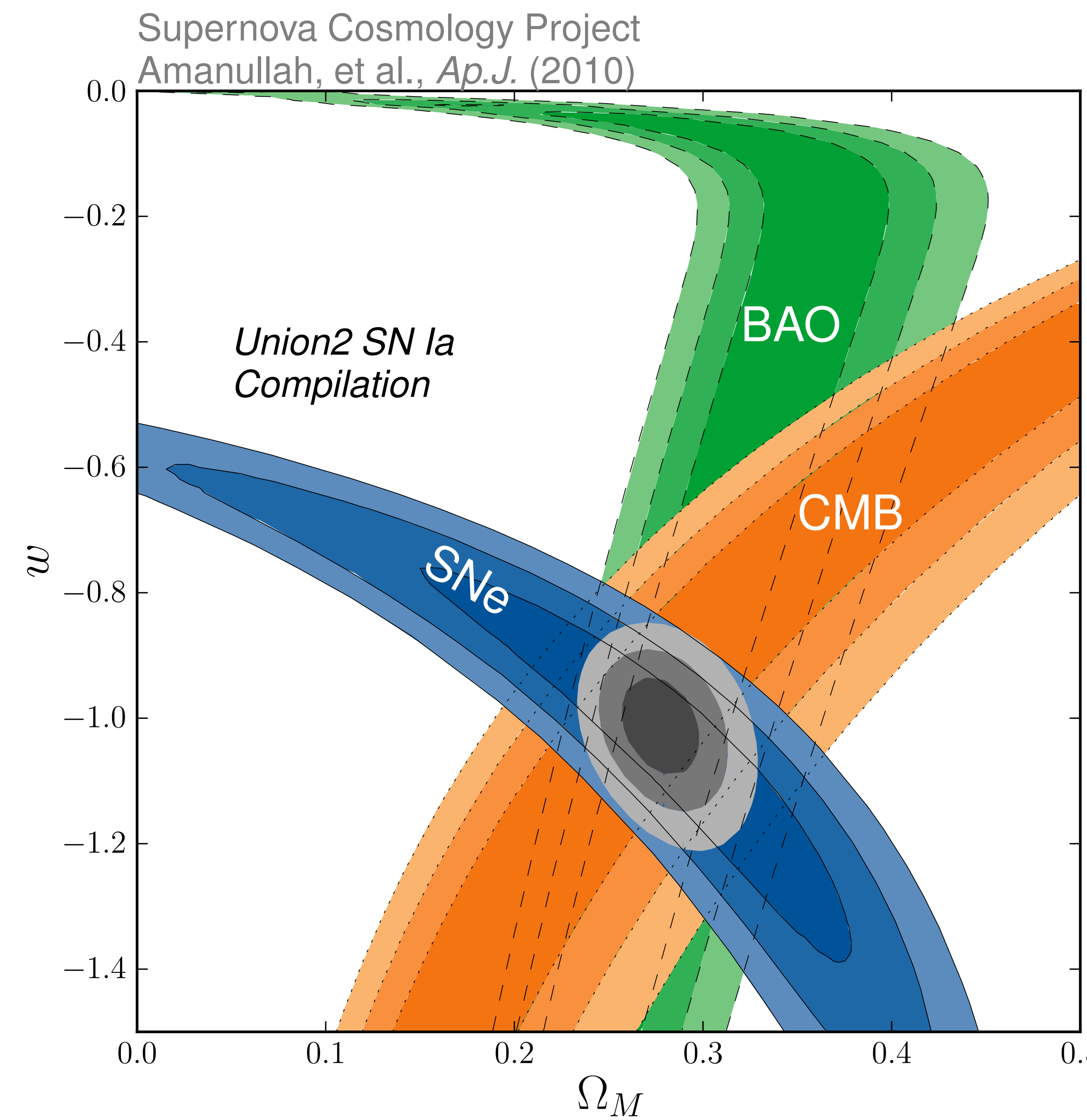
Growth of Cosmic Structure: the Next Frontier

Dragan Huterer
Physics Department
University of Michigan

[On sabbatical at MPA Garching, Jan-Aug 2015]



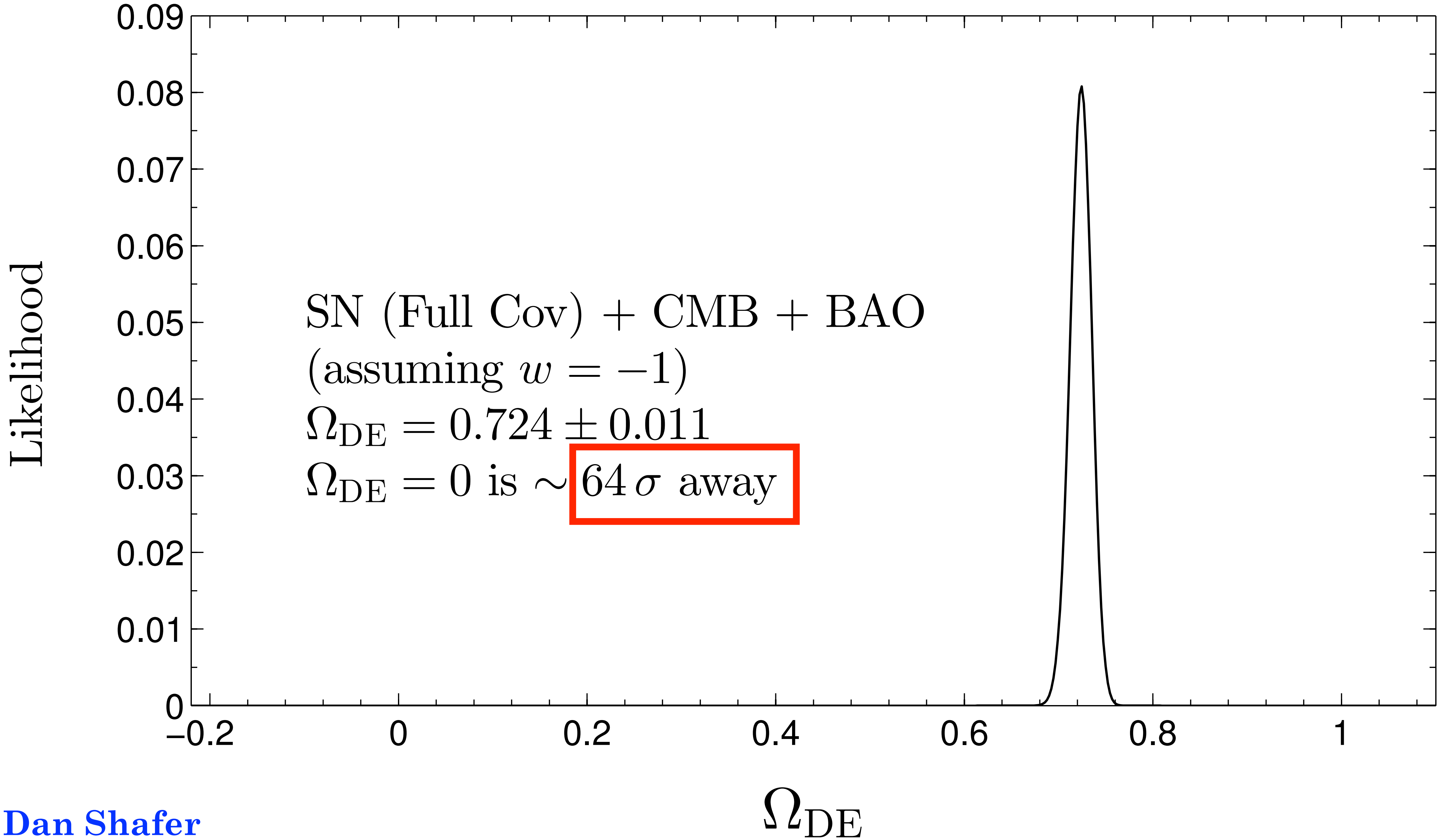


$$\Omega_{\rm DE} \equiv \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

$$w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

Current evidence for dark energy is impressively strong

Current evidence for dark energy is impressively strong



Dan Shafer
(Michigan grad student)

Big questions

1. Is the cosmic acceleration due to something other than vacuum energy?

2. Does GR self-consistently describe the acceleration?

Wish List

Goals:

Measure $\Omega_{\rm DE}, w$

Measure $\rho_{\rm DE}(z)$ or $w(z)$

Measure any clustering of DE

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

$$\Omega_{\rm DE} = \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

A difficulty:

DE theory target accuracy, in e.g. w(z), not known *a priori*

Contrast this situation with:

A difficulty:

DE theory target accuracy, in e.g. w(z), not known *a priori*

Contrast this situation with:

1. Neutrino masses:

$$\left.\begin{aligned}(\Delta m^2)_{sol} &\simeq 8\times10^{-5}\ \mathrm{eV}^2\\ (\Delta m^2)_{atm} &\simeq 3\times10^{-3}\ \mathrm{eV}^2\end{aligned}\right\}$$

$\sum m_i = 0.06\ \mathrm{eV}^*$ (normal)

vs.

$\sum m_i = 0.10\ \mathrm{eV}^*$ (inverted)

*(assuming m_3=0)

A difficulty:

DE theory target accuracy, in e.g. w(z), not known *a priori*

Contrast this situation with:

1. Neutrino masses:

$$\left.\begin{array}{l}(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ \mathrm{eV}^2 \\ (\Delta m^2)_{atm} \simeq 3\times10^{-3}\ \mathrm{eV}^2\end{array}\right\} \quad \begin{array}{l}\sum m_i = 0.06\ \mathrm{eV}^* \ \text{(normal)} \\ \text{vs.} \\ \sum m_i = 0.10\ \mathrm{eV}^* \ \text{(inverted)}\end{array}$$

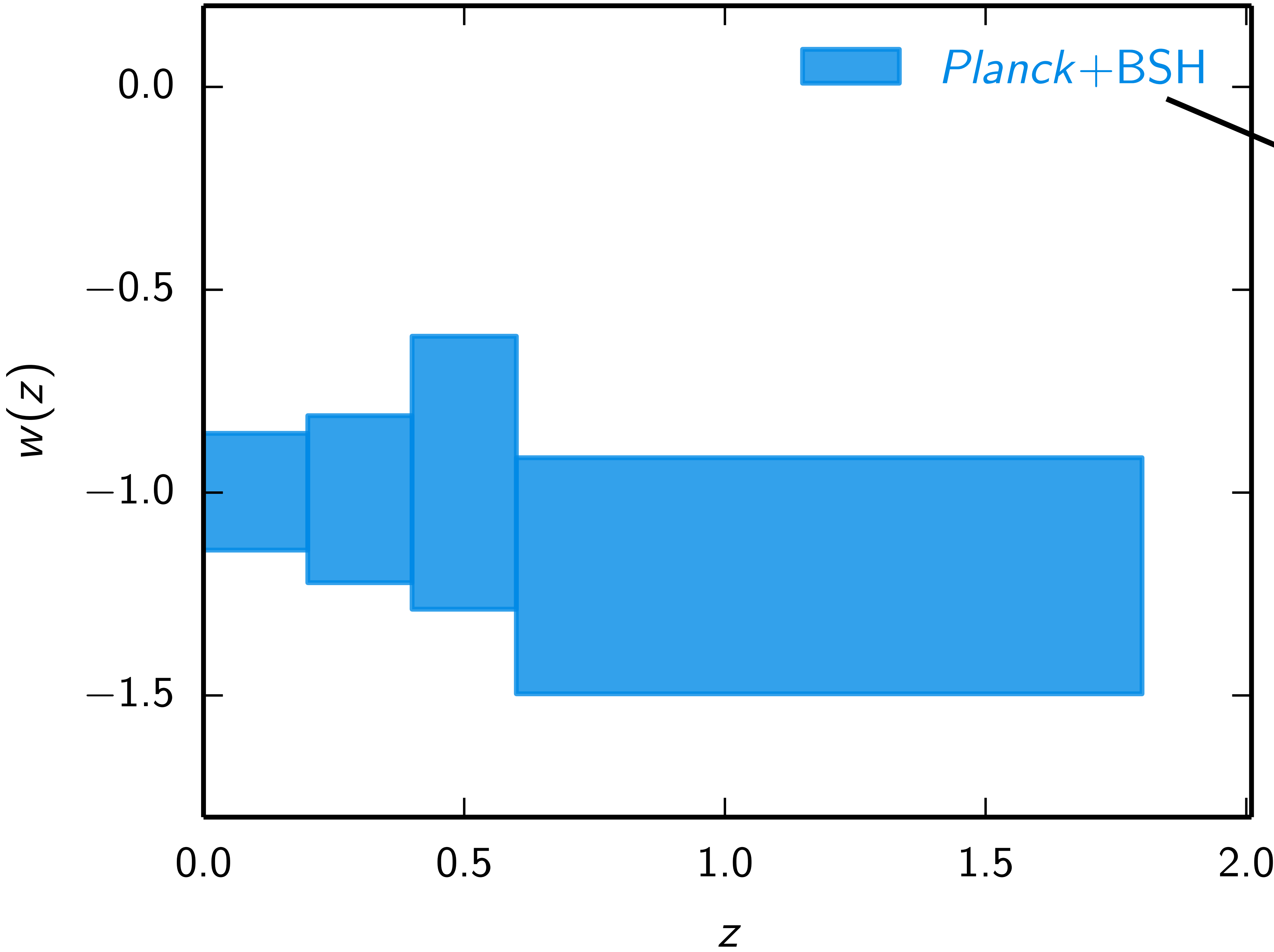
*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

$$m_H \lesssim O(200)\ \mathrm{GeV}$$

(assuming Standard Model Higgs)

Current constraints on w(z): **largely from geometrical measures**



BAO+
SNIa+
Hubble const

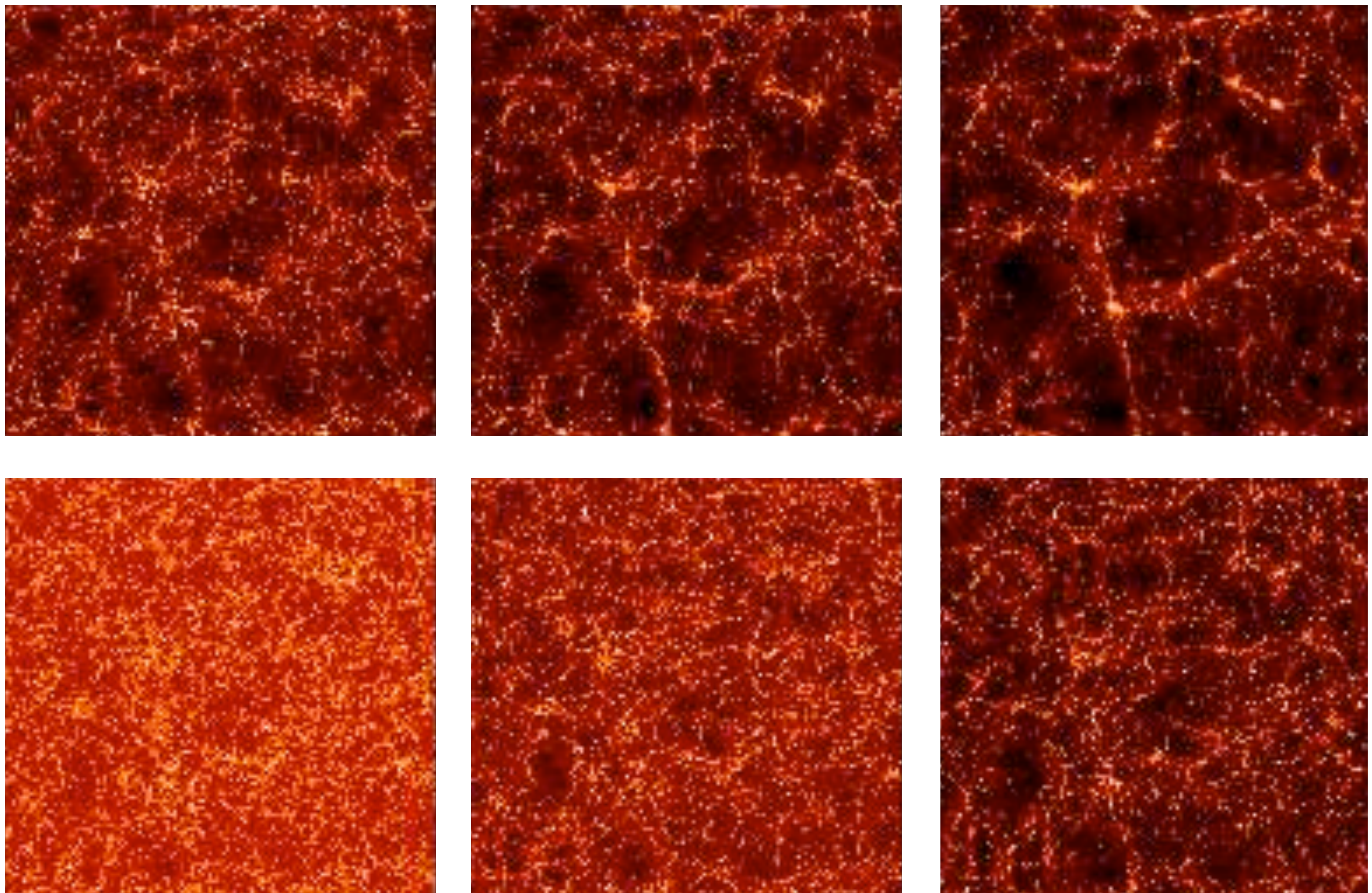
Planck XIV, "Dark Energy and Modified Gravity", arXiv:1502.01590

Dark Energy suppresses the growth of density fluctuations

(a=1/4 or z=3) 1/4 size of today | (a=1/2 or z=1) 1/2 size of today | (a=1 or z=0) Today

with DE

without DE



Huterer et al, Snowmass report, 1309.5385

The Virgo Consortium (1996)

Using growth to separate GR from MG:

For example:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

↓ Modified gravity

↓ GR + dark energy

Growth of density fluctuations can decide:

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_M\delta = 0$$

(assuming GR)

LSS tracers and their statistical probes

- Clusters of galaxies
  - 1-point function - cluster counts (dn/dlnM), sens to DE
  - 2-pt function - sensitive to primordial NG
- Galaxies: LRG, ELG, also quasars
  - 2-point function: pretty well understood, easily measured
  - anisotropic 2-pt function - Redshift Space Distortions (RSD)
  - 3-pt function: powerful, but issues in predicting $b_G(k, a, env)$
  - also galaxy-CMB cross-correlation
- Weak Lensing Shear:
  - 2-point function: measurements systematics dominated
  - 3-pt function: future; systematics a huge challenge
  - also gal-gal (γ-g), shear peaks, ...

Counting galaxy clusters

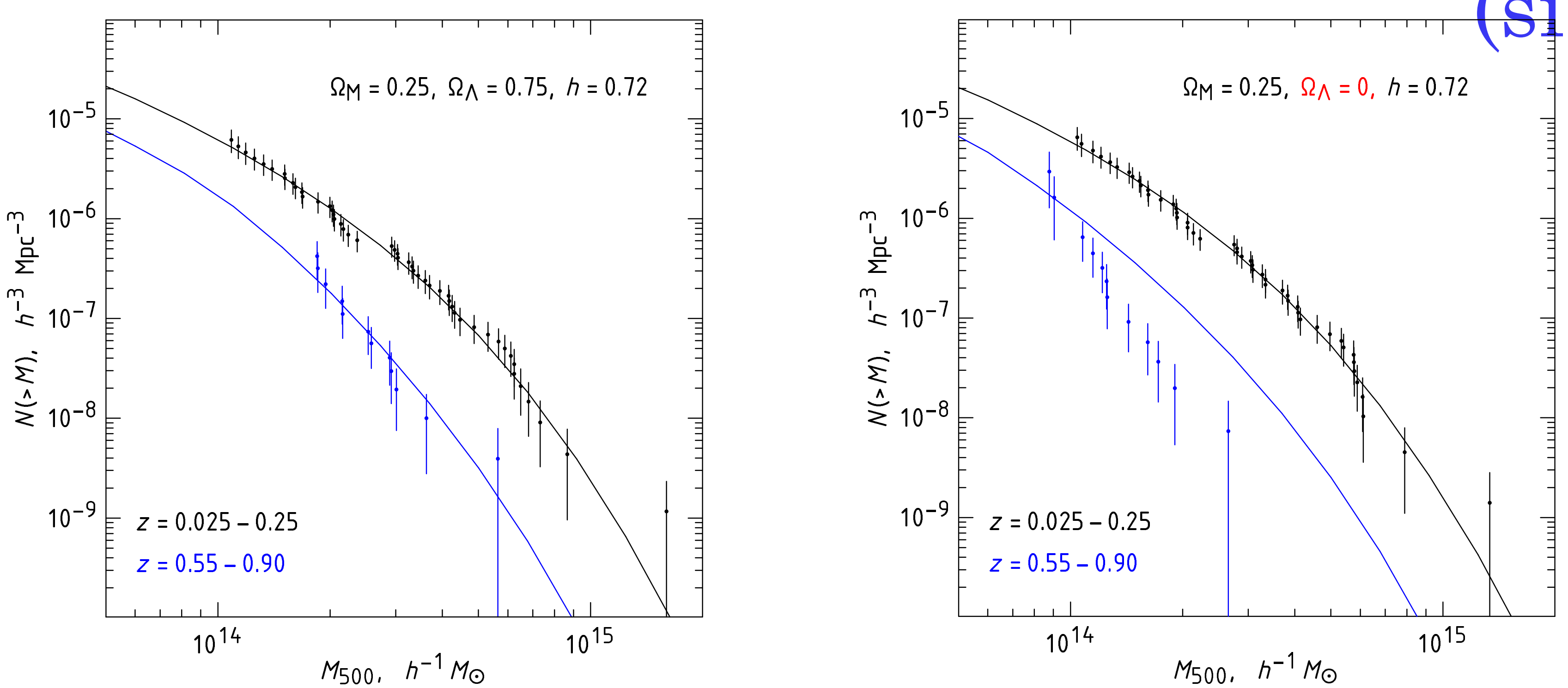
Allen, Evrard & Mantz review, 2011

cluster number
(measure)

$$\frac{d^2N}{d\Omega\,dz} = n(z)\,\frac{r(z)^2}{H(z)}$$

cluster num. density
(simulations)

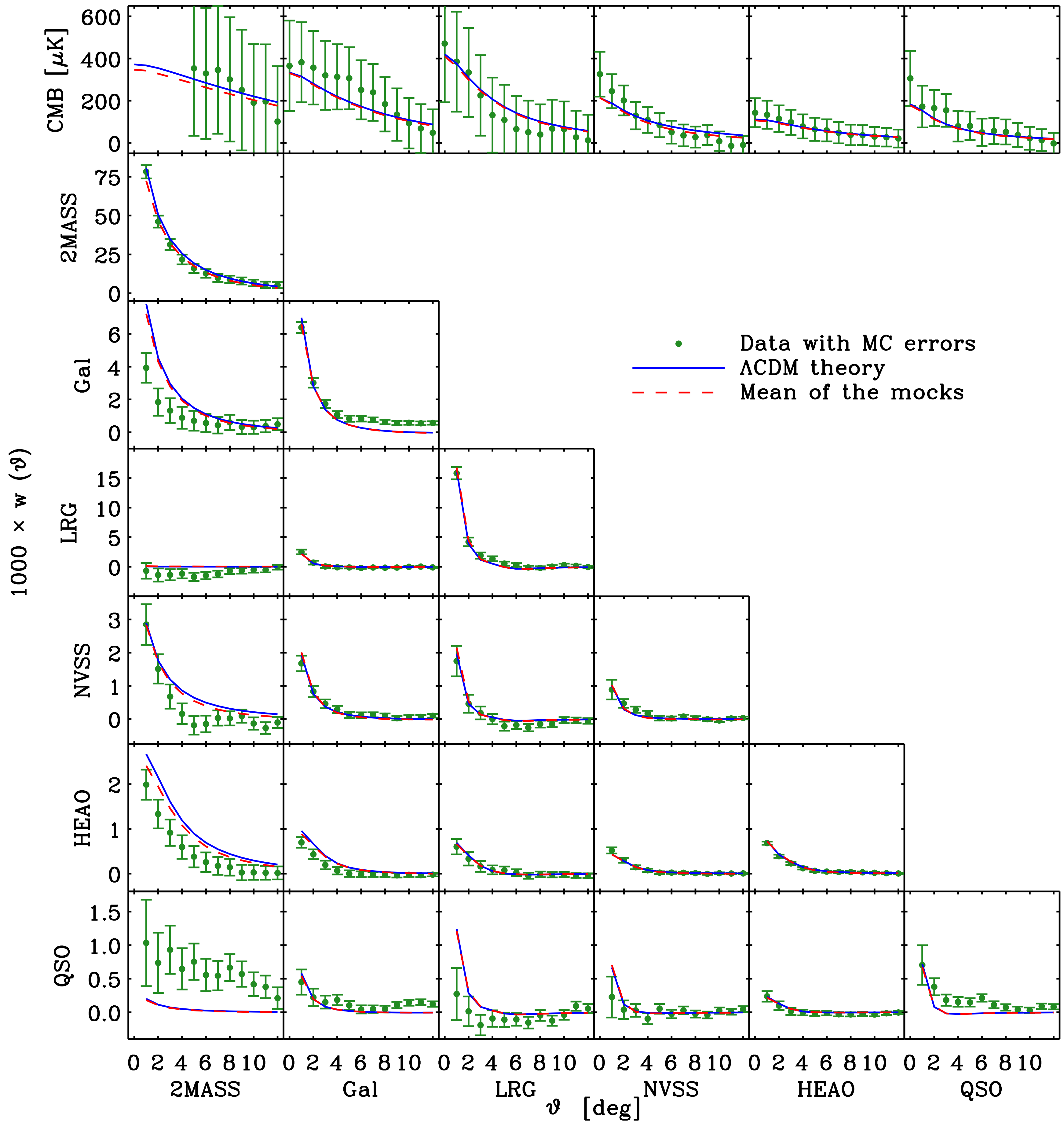
distance factors
(theory)



Vikhlinin et al, 2009

“Cross - correlations”:

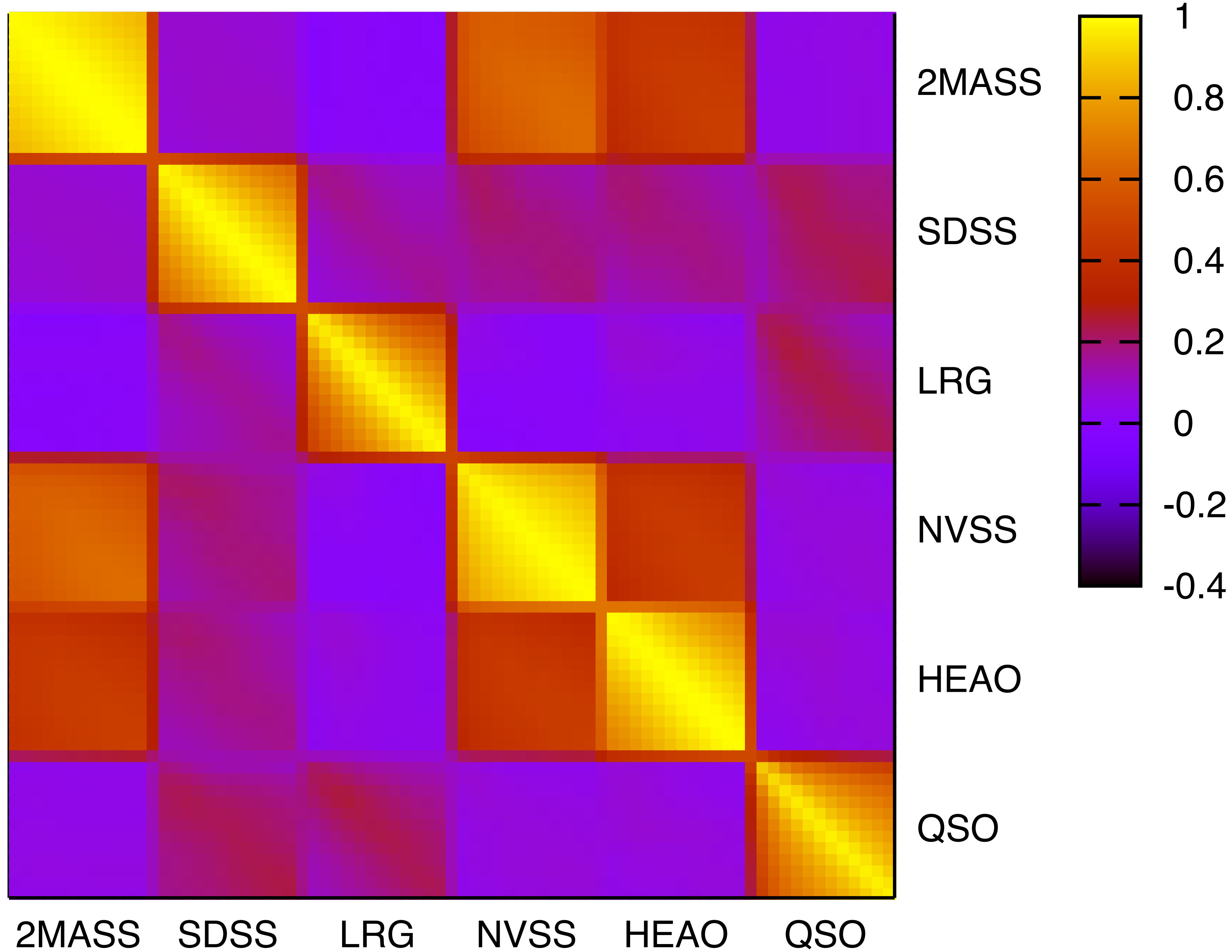
galaxy - galaxy
galaxy - QSO
galaxy - CMB
shear -shear
shear-galaxy
apple - orange
.....



Giannantonio et al. 2013

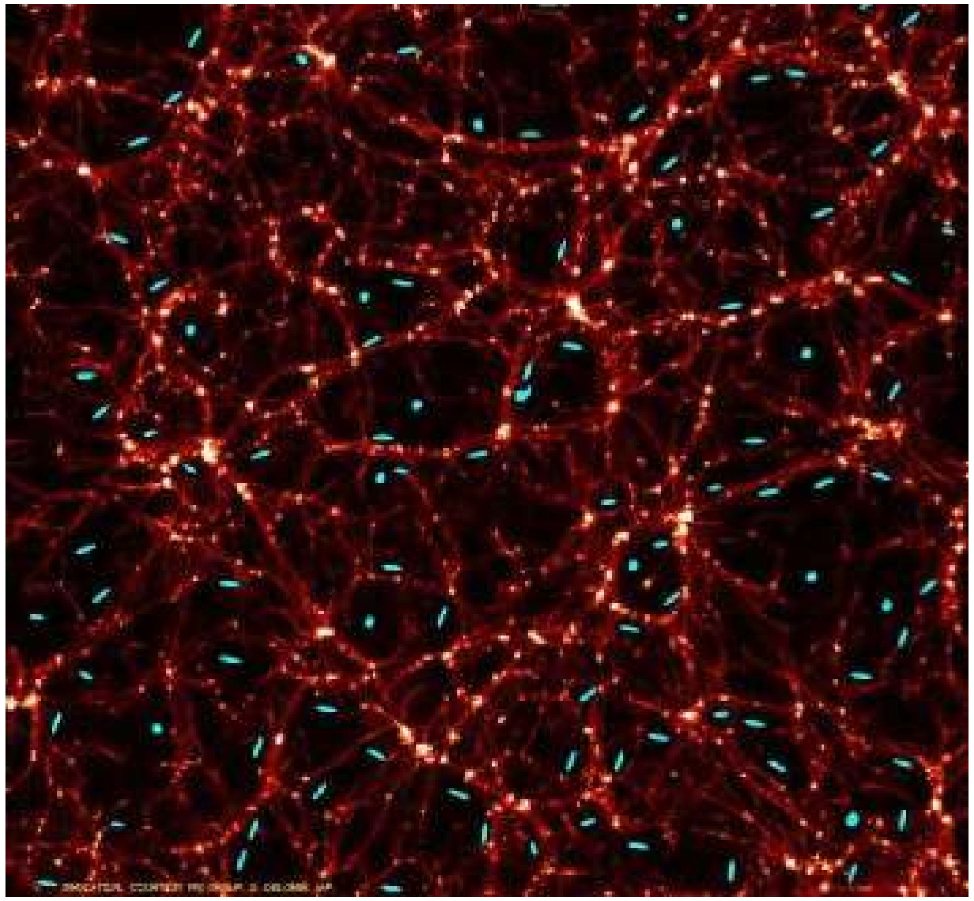
Hardest part of this:
simulating/calculating the covariance matrix

(that is: clustering in nonlinear regime)

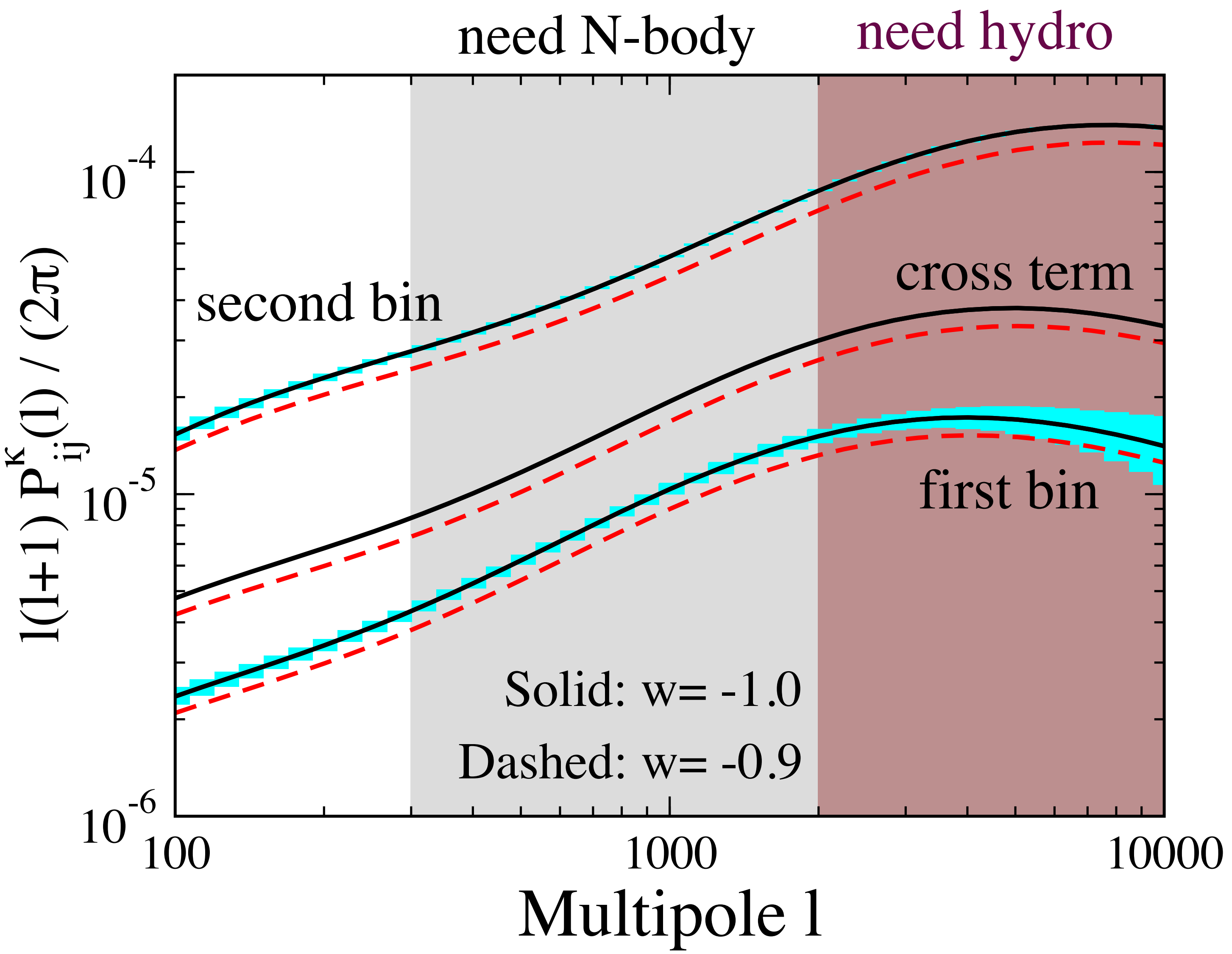


Giannantonio et al. 2013

Weak Gravitational Lensing



Takashi Hamana

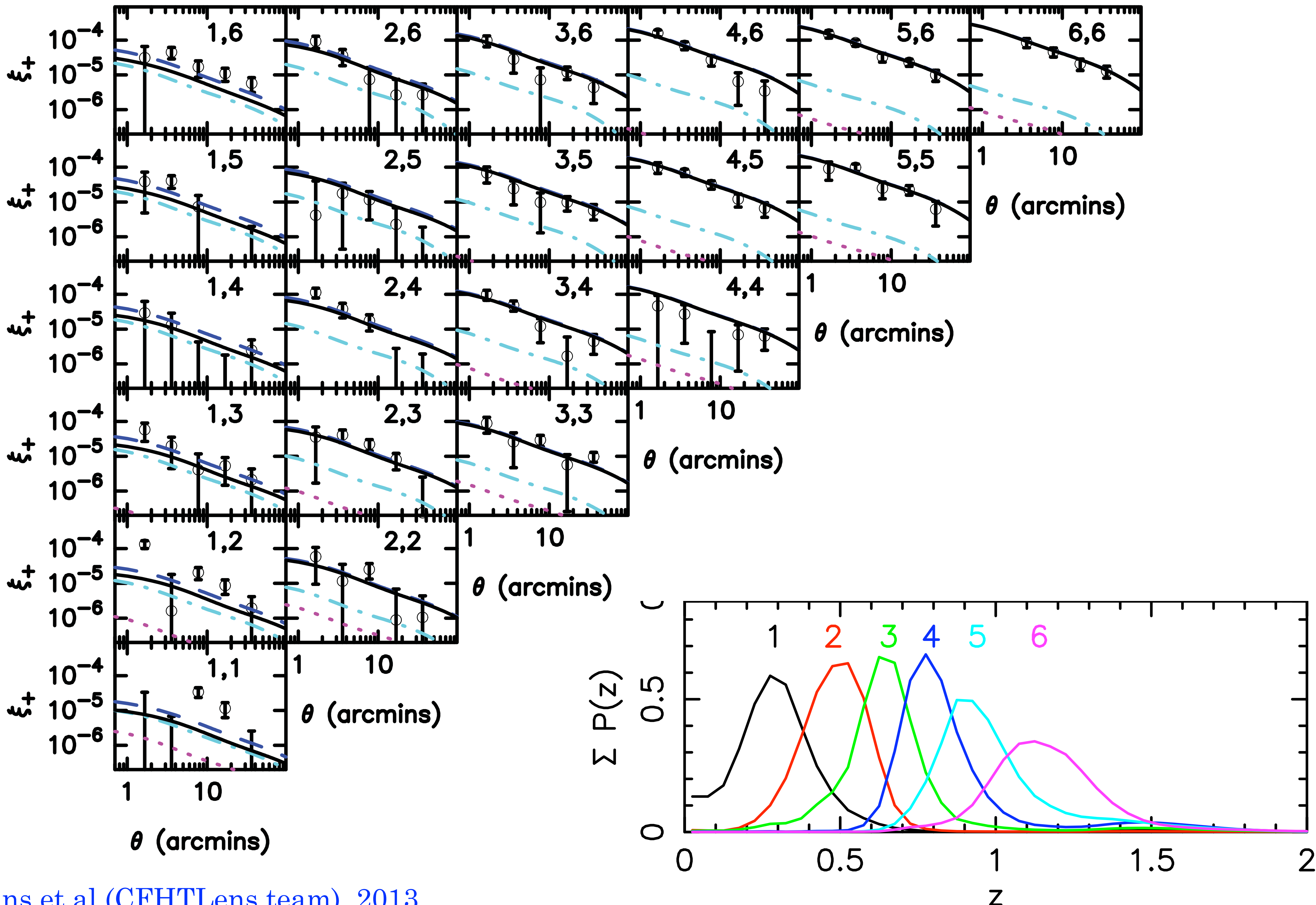


Huterer et al, Snowmass report, 1309.5385

WL systematics are very challenging:

$$\gamma^{\rm obs} = \gamma^{\rm true}(1+m) + \gamma^{\rm add} + \gamma^{\rm noise}$$

Measured 2-pt correlation func from CFHTLens



Heymans et al (CFHTLens team), 2013

Next Frontier: **Growth (+geom) from LSS**

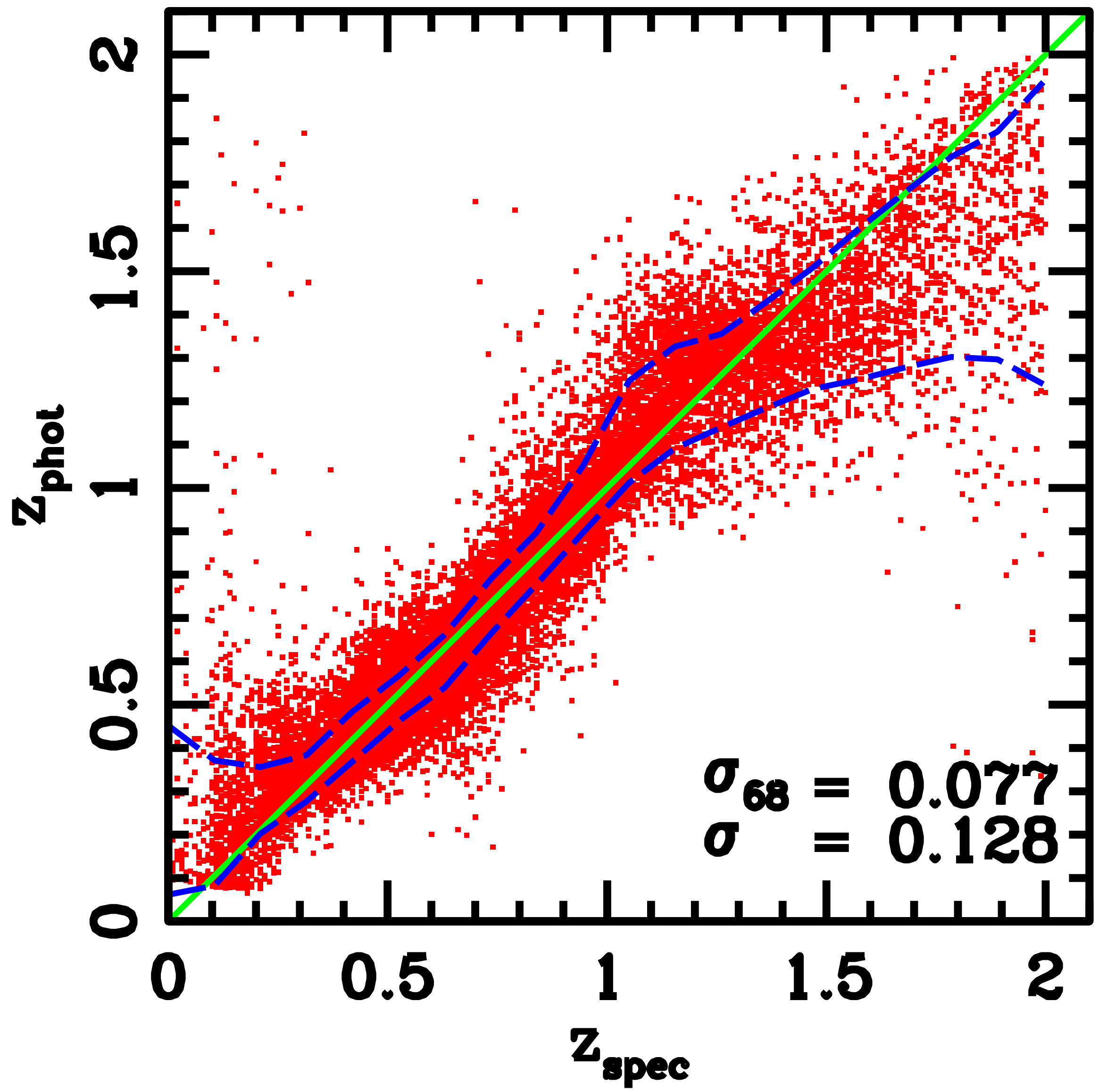
	CMB	LSS
dimension	2D	3D
# modes	$\propto l_{max}^2$	$\propto k_{max}^3$
can slice in	λ only	λ, M, bias...
temporal evol.	no	yes
systematics?	relatively clean	relatively messy
theory modeling	easy	can be hard

Systematic Errors, top two:

1. Photometric Redshift errors
2. (photometric) Calibration errors

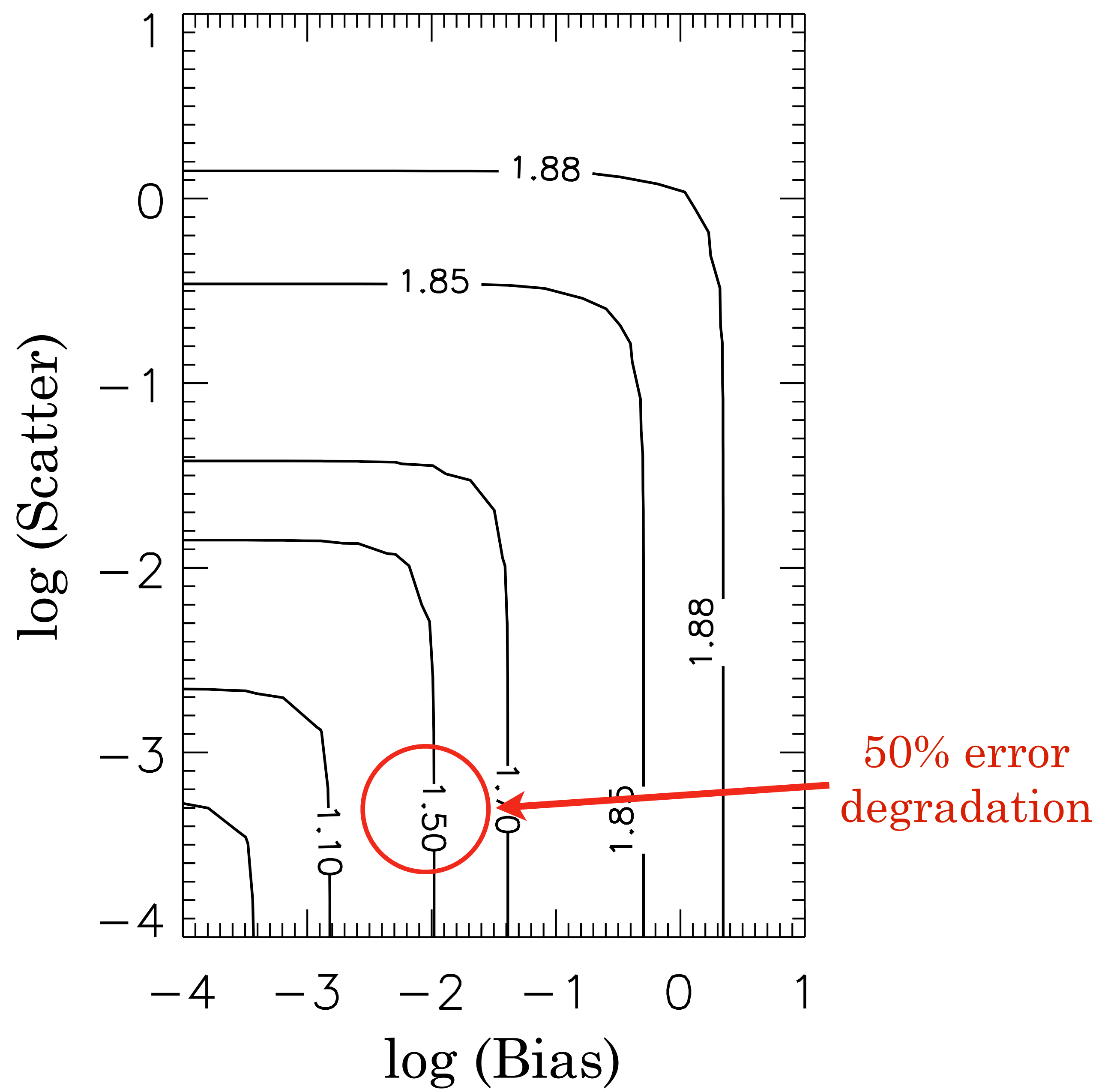
Poster child for the systematics: photometric redshift errors

z_{phot}-z_{spec}
from "training set"



C. Cunha

Requirements

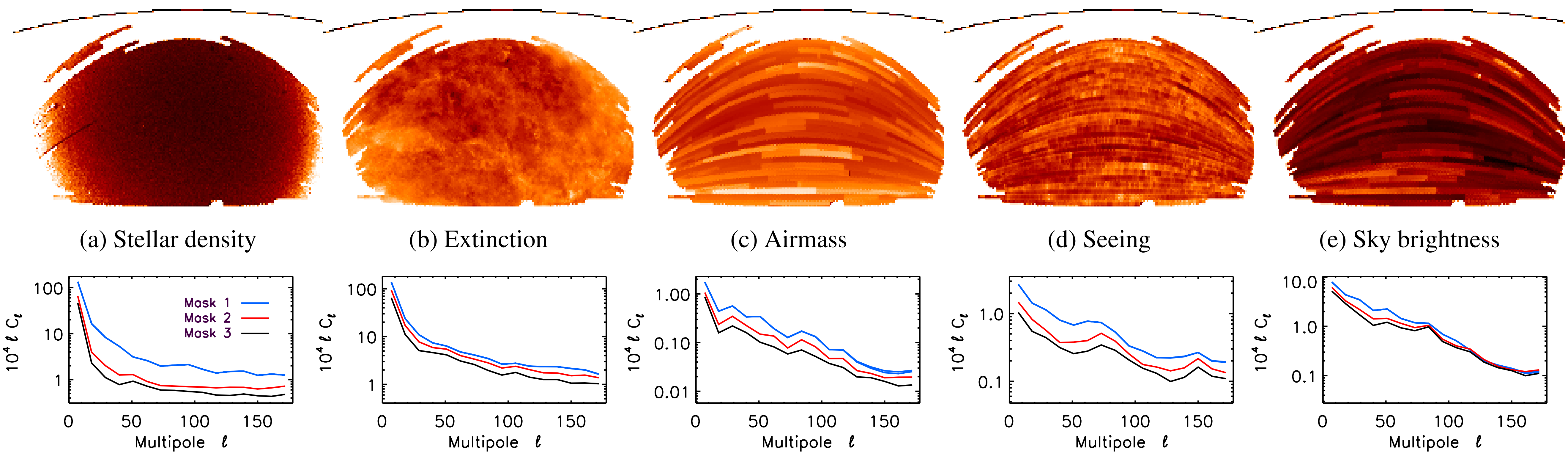


Ma, Hu & Huterer 2006

(Photometric) **calibration** errors

- **Detector sensitivity**: sensitivity of the pixels on the camera vary along focal plane.
- **Observing conditions**: spatial and temporal variations.
- **Bright objects**: The light from foreground bright stars and galaxies.
- **Dust extinction**: Dust in the MW absorbs light from the distant galaxies.
- **Star-galaxy separation**: Faint stars erroneously included in the galaxy sample.
- **Deblending**: Galaxy images can overlap.

Huterer, Cunha & Fang 2013
Shafer & Huterer 2015



Leistedt et al 2013

Explicitly separating information from growth and geometry using current data

Ruiz & Huterer, PRD 2015, arXiv:1410.5832

Sensitivity to geometry and growth

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$
RSD	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

Idea: compare geometry and growth

e.g. Wang, Hui, May & Haiman 2007

Our approach:

Double the standard DE parameter space

($\Omega_M = 1 - \Omega_{DE}$ and w):

$\Rightarrow \Omega_M^{geom}, w^{geom}$ $\Omega_M^{grow}, w^{grow}$

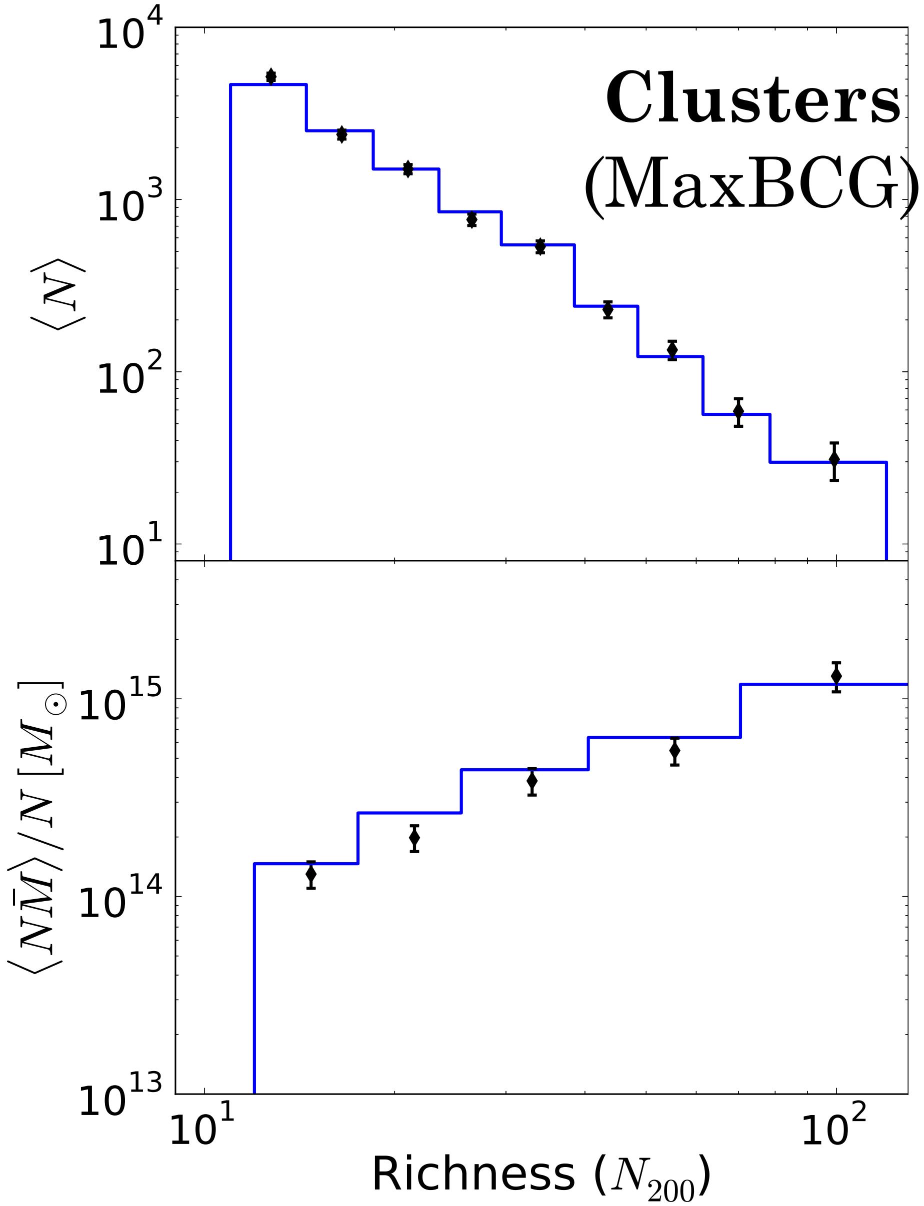
[In addition to other:

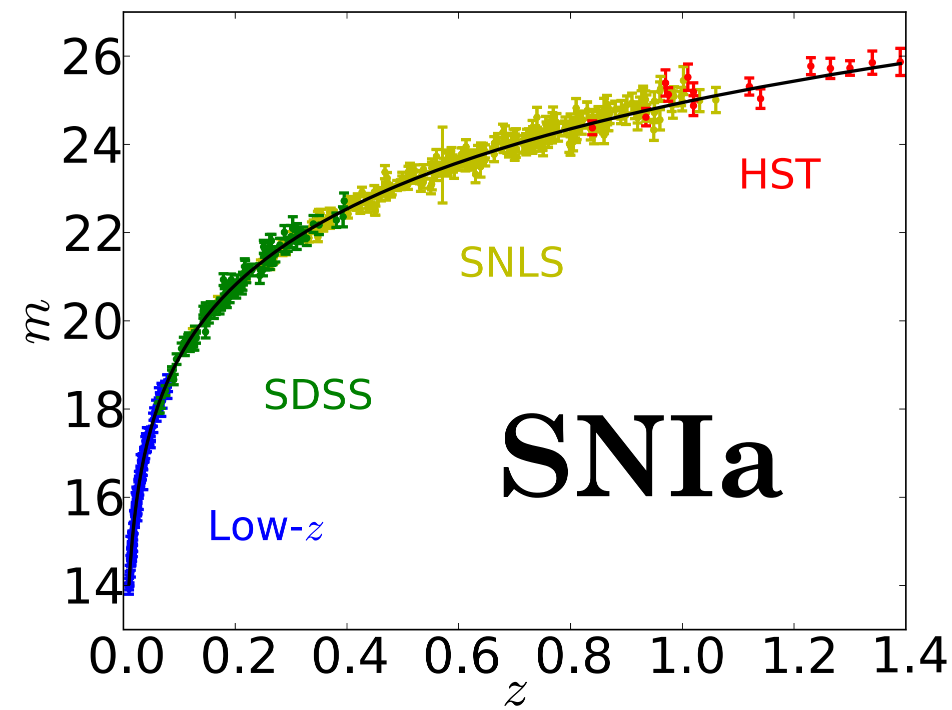
standard parameters: $\Omega_M h^2$ $\Omega_B h^2$, n_s, A)

nuisance parameters: probe-dependent]

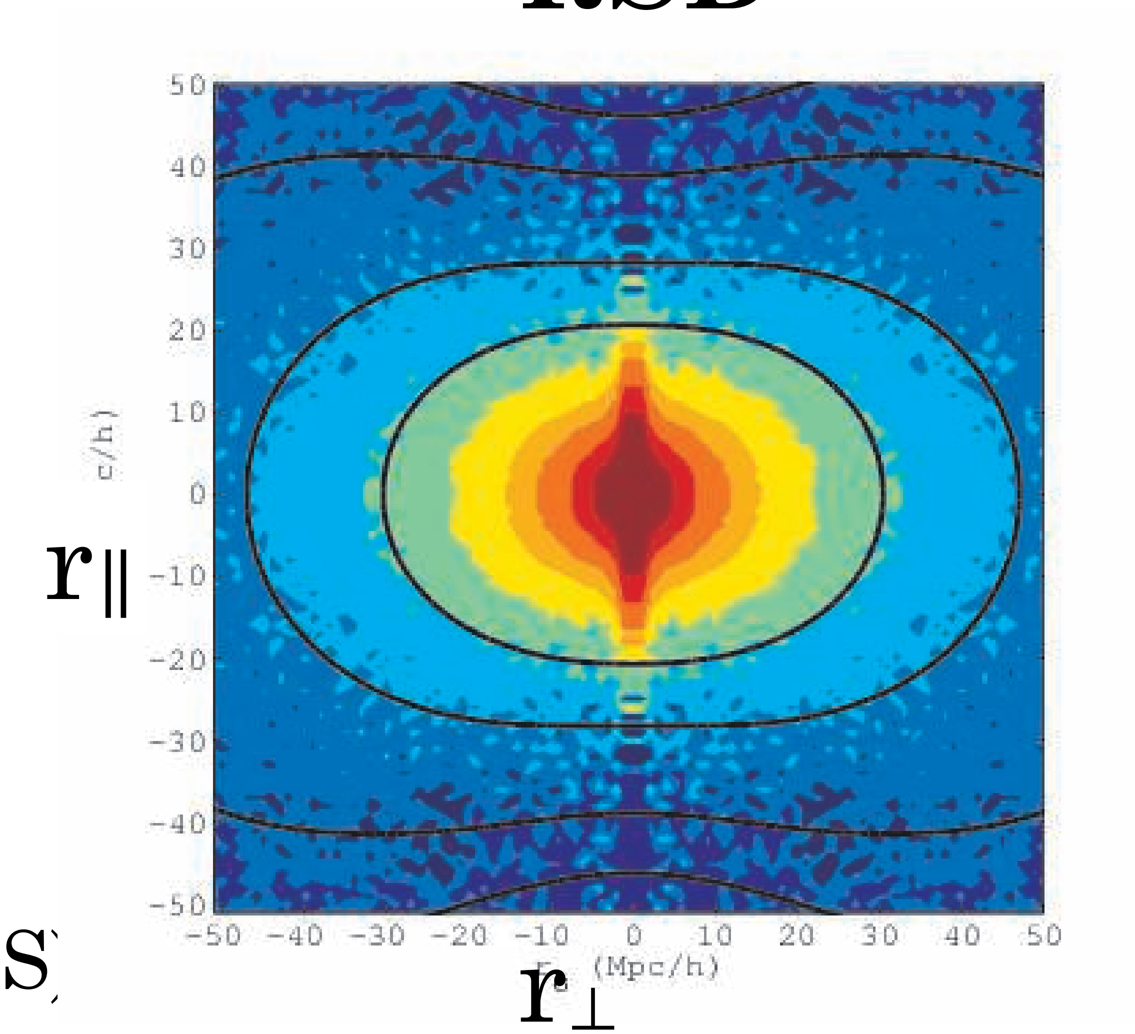
Ruiz & Huterer, 2015

(Current) Data used





RSD

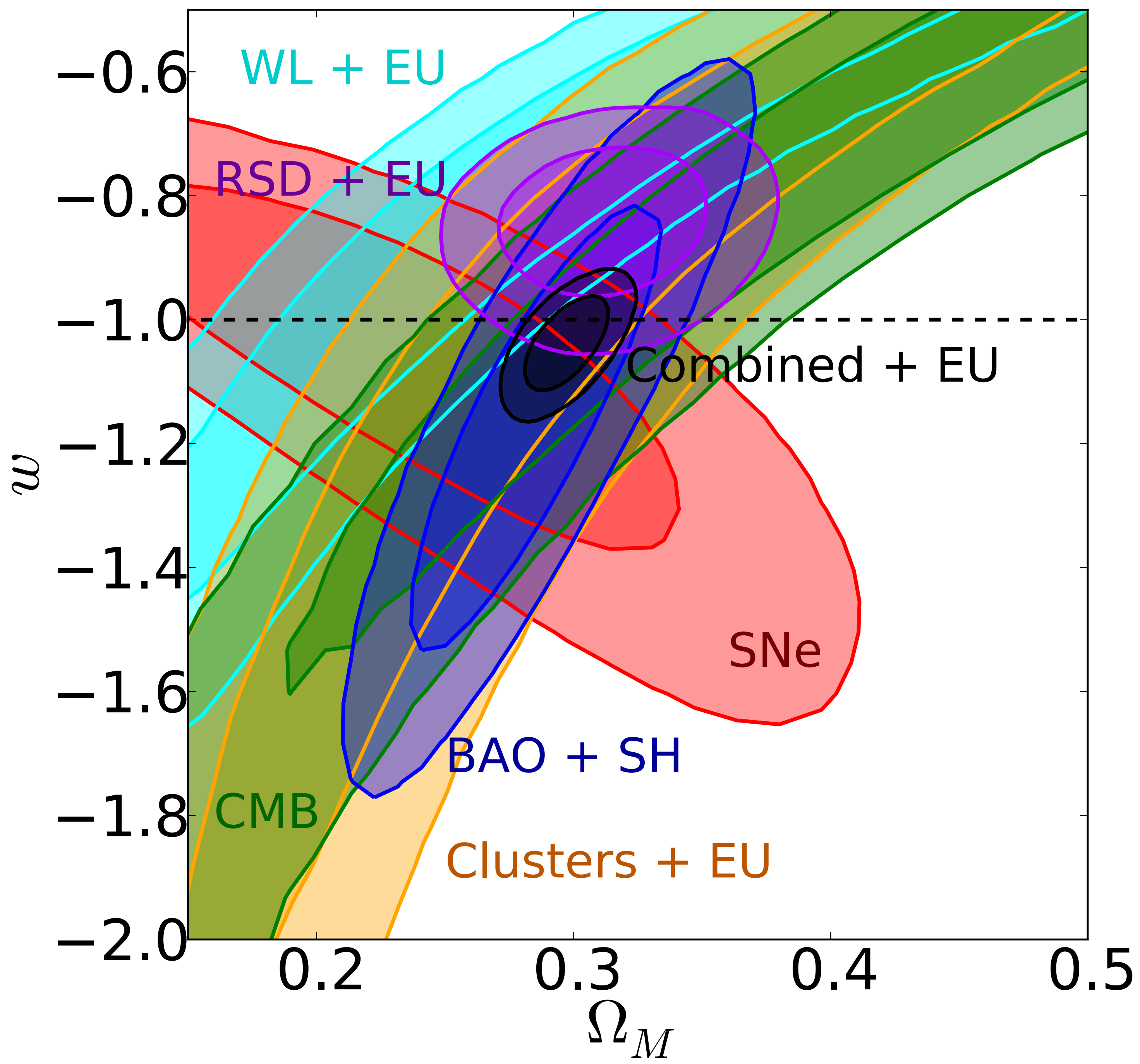


CMB (Planck peak location)

Weak Lensing (CFHTLens)

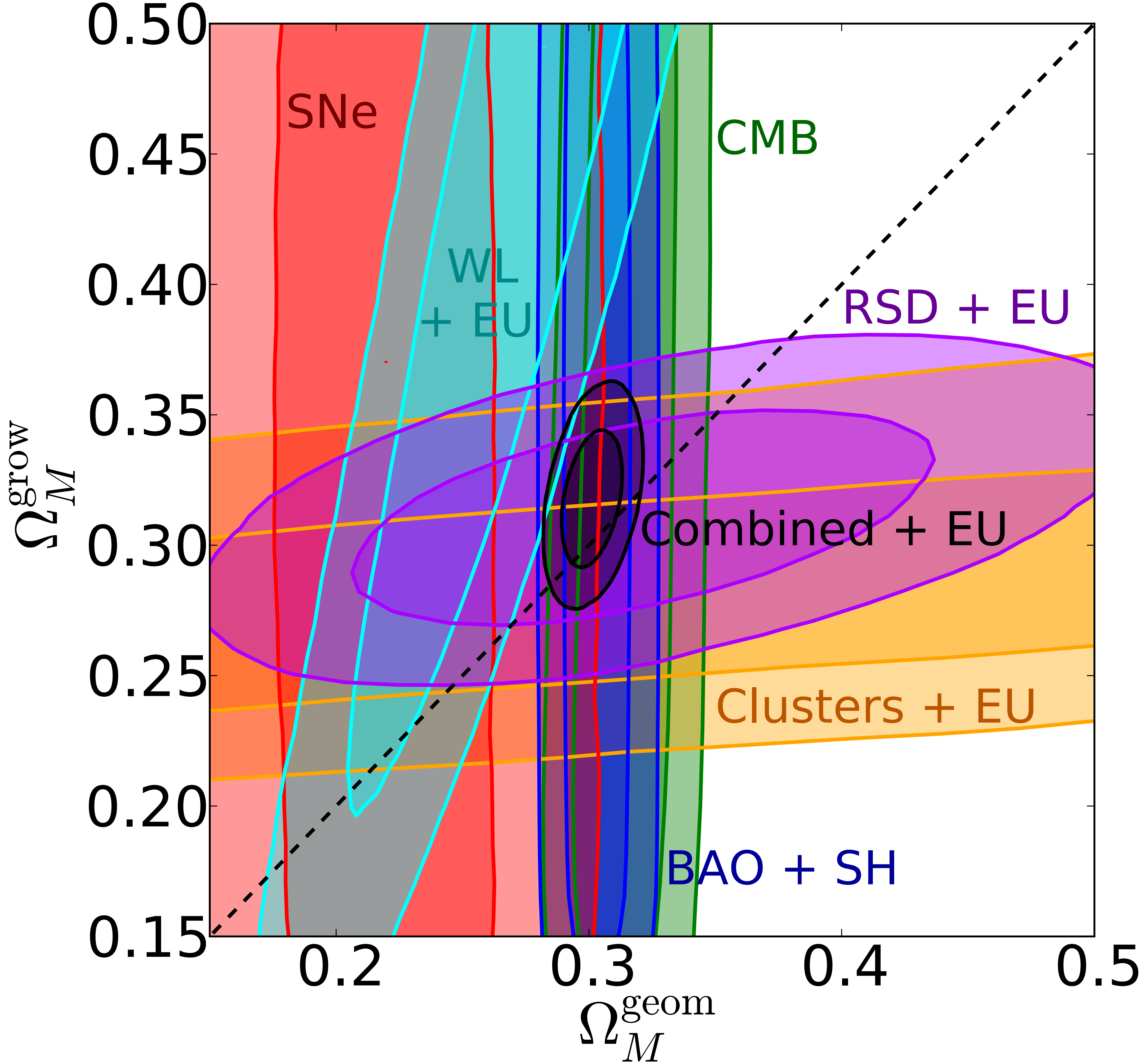
BAO (6dF, SDSS LRG, BOSS CMASS)

Standard parameter space



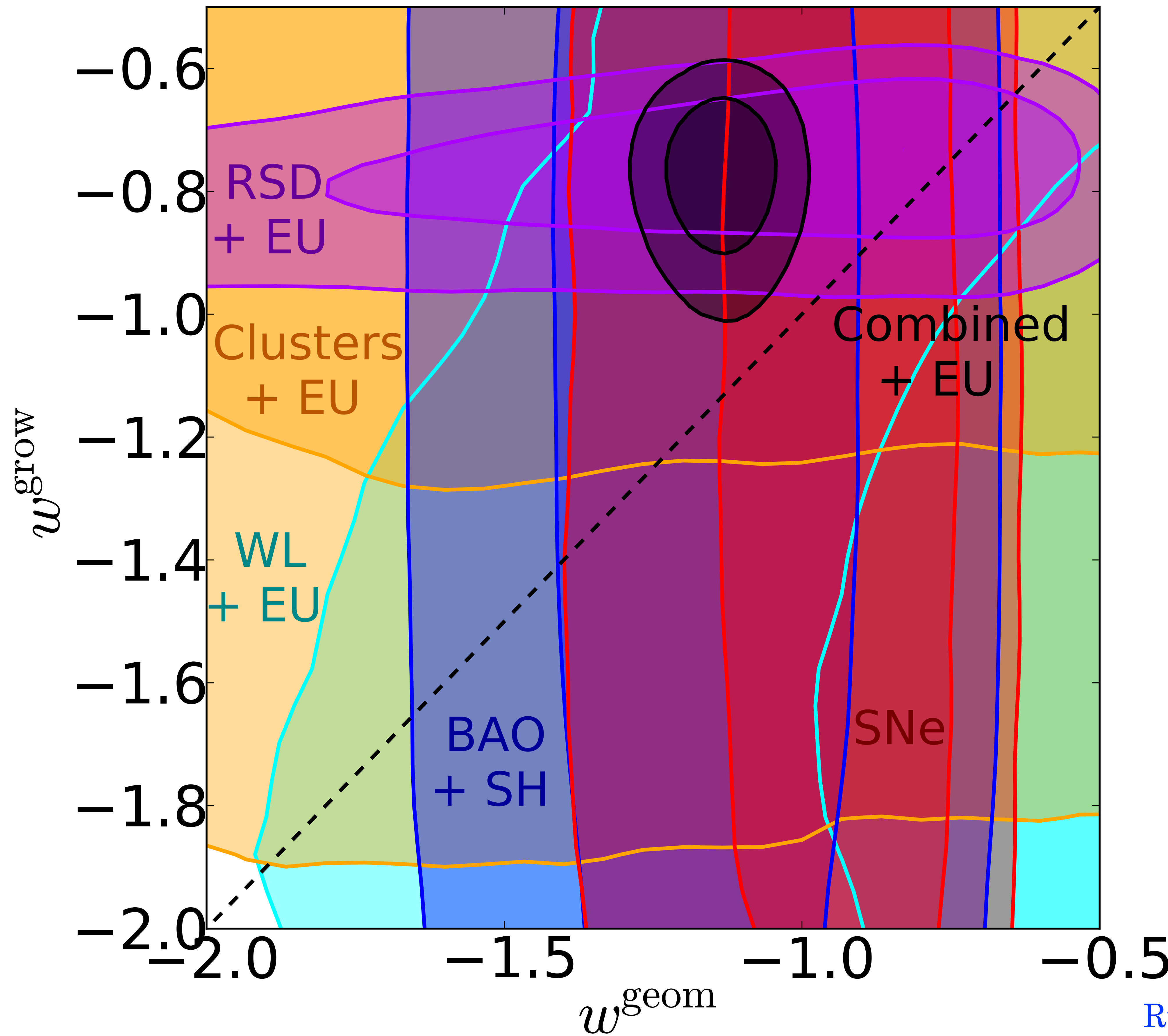
EU = Early Universe prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$, n_s, A)
SH = Sound Horizon prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$)

Omega matter: geometry vs. growth



* SN not the recalibrated JLA compilation - need to update; will move $\Omega_M{}^{\rm grow}$ up

w (eq of state of DE): geometry vs. growth



Evidence for $w^{grow} > w^{geom}$: 3.3-σ

Ruiz & Huterer, 2015

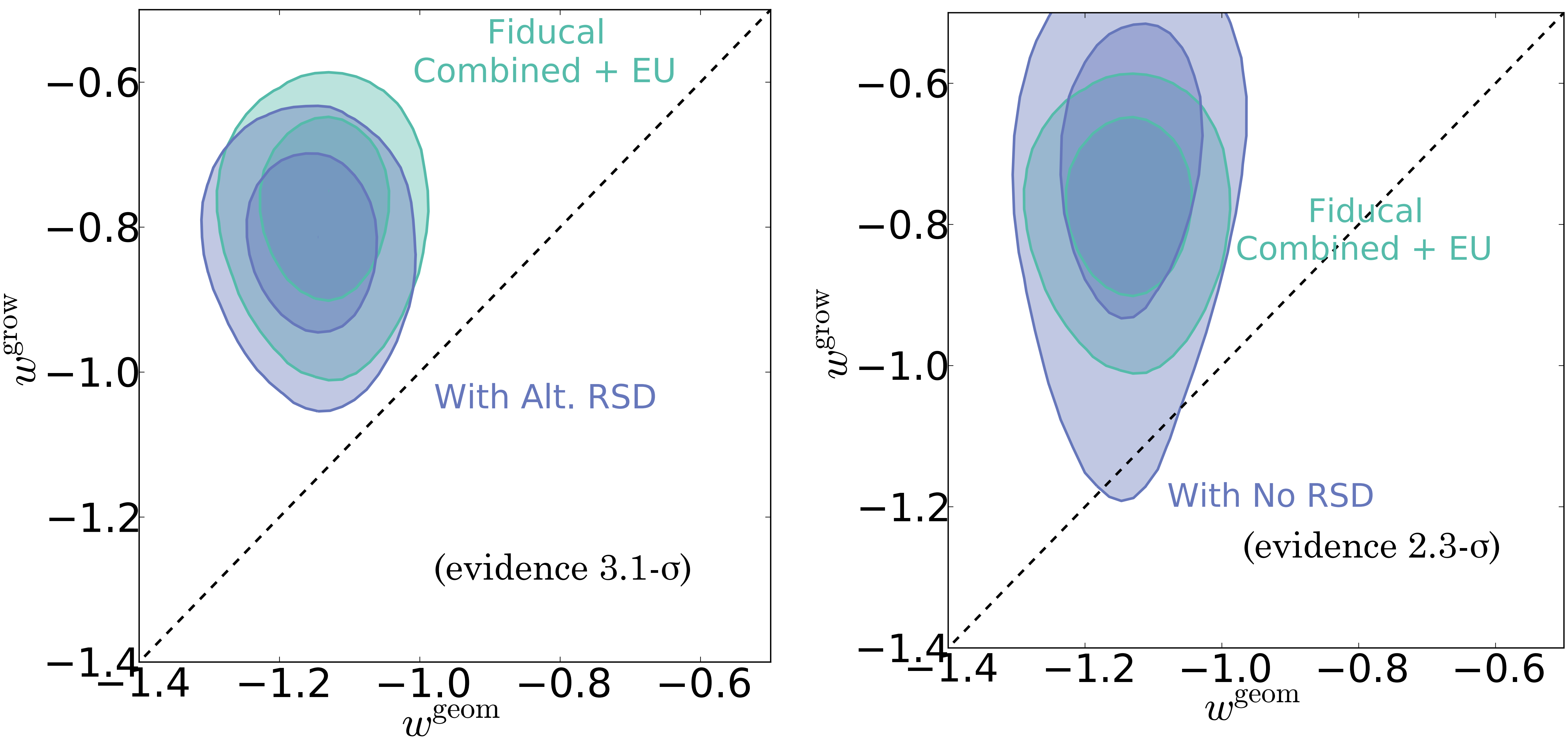
Therefore:
growth probes point to even less growth than LCDM with ~Planck parameters
(i.e. $w^{grow} > -1$)

(but the evidence is still not very strong...)

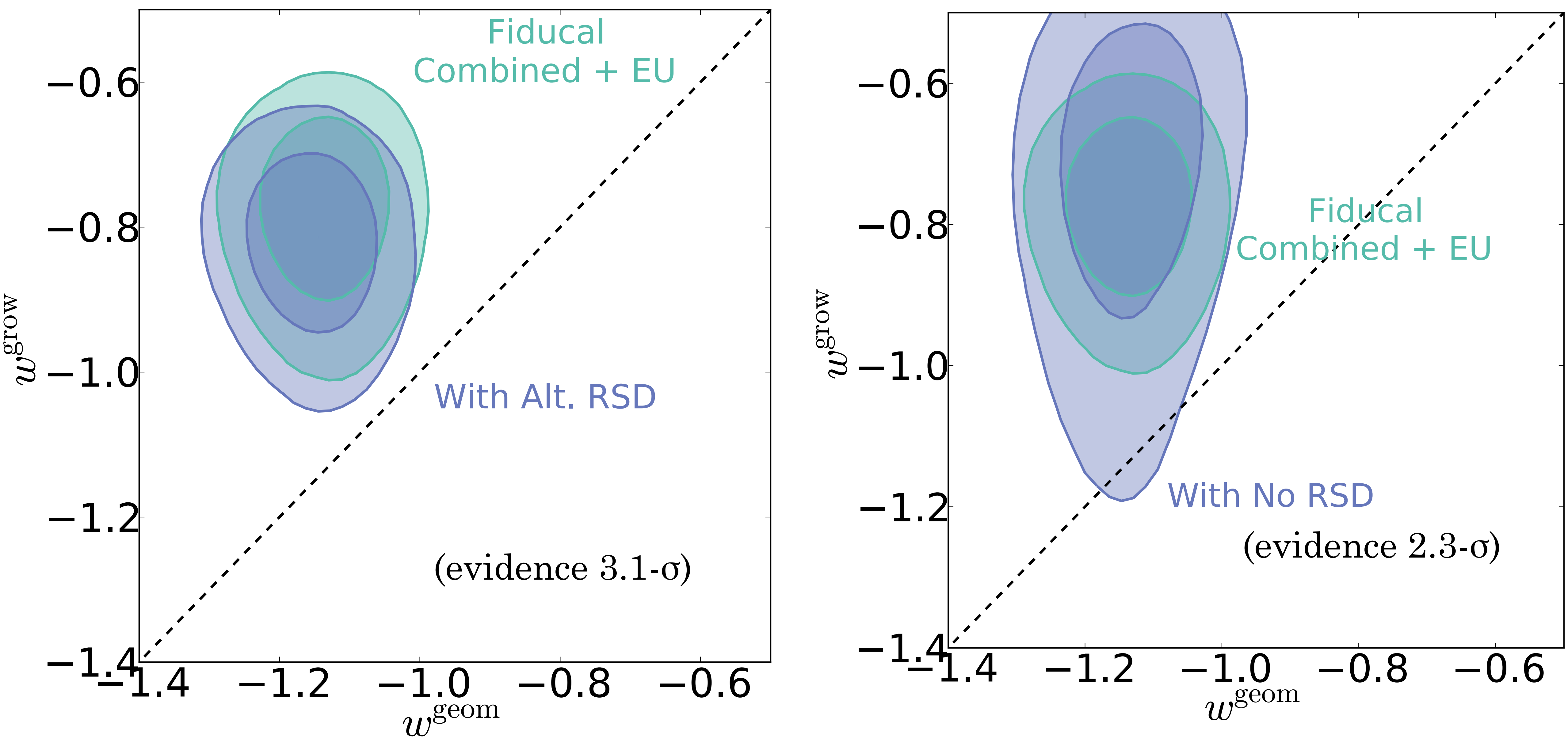
Probably equivalent to these recent findings:

- σ_8 from clusters is lower than that from CMB (eg. Hou et al, Bocquet et al, Costanzi et al)
- σ_8 from WL is lower than that from CMB (eg. MacCrann et al)
- evidence for neutrino mass (eg. Beutler et al, Dvorkin et al)
- evidence for interactions in the dark energy sector (eg. Salvatelli et al)

RSD prefer $w^{grow} > -1$ (slower growth than in LCDM)



RSD prefer $w^{grow} > -1$ (slower growth than in LCDM)



“Are there cracks in the Cosmic Egg?”

Michael Turner, Aspen, summer 2014

Dark Energy Survey Instrument (**DESI**)

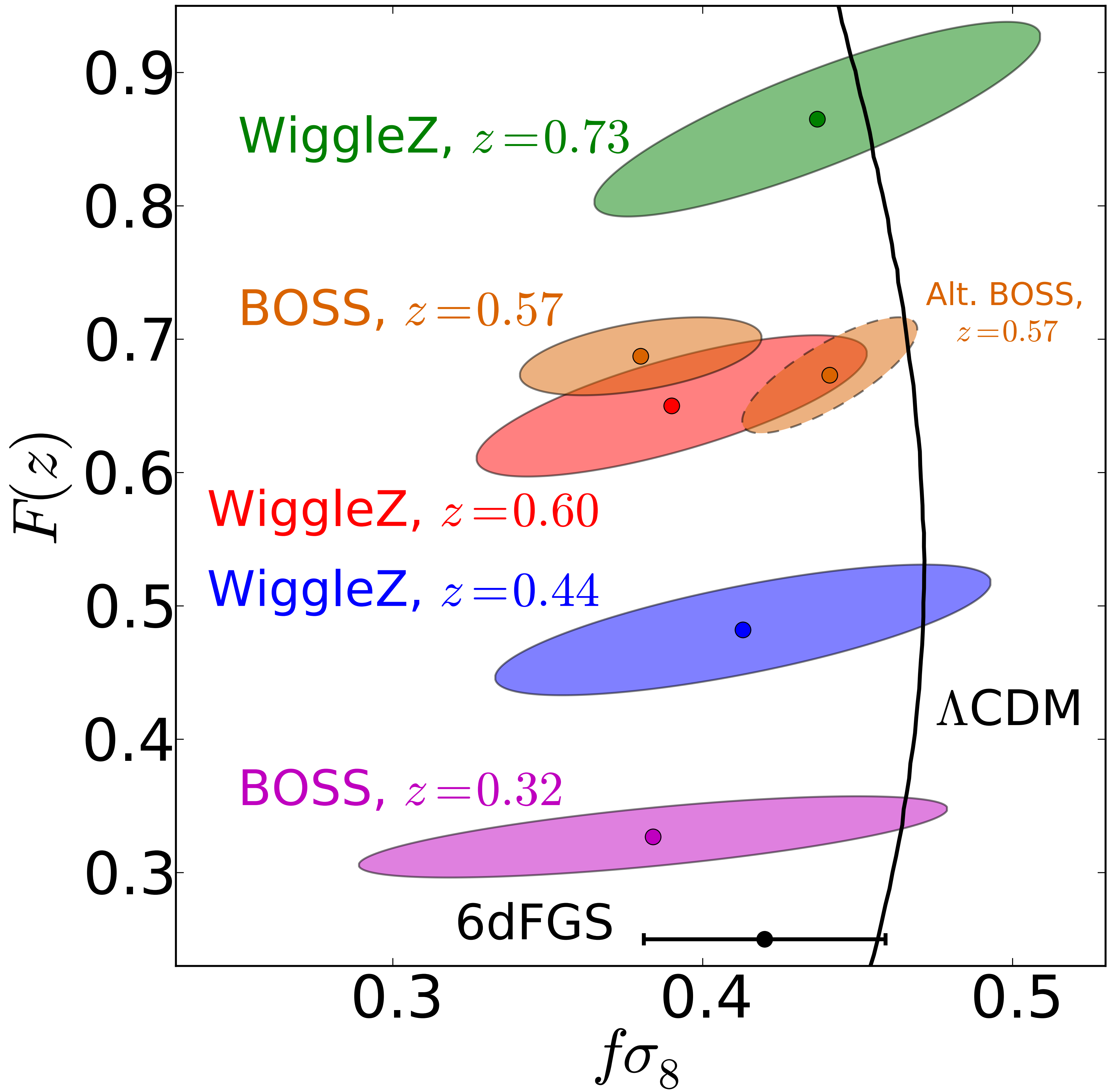
- Huge spectroscopic survey on Mayall telescope (Arizona)
- ~5000 fibres, ~15,000 sqdeg, ~30 million spectra
- LRG in $0 < z < 1$, ELG in $0 < z < 1.5$, QSO $2.2 < z < 3.5$
- Great for dark energy (RSD, BAO)
- Great for primordial non-Gaussianity - $P(k, z)$, bispectrum…
- Start ~2018, funding DOE + institutions

Conclusions

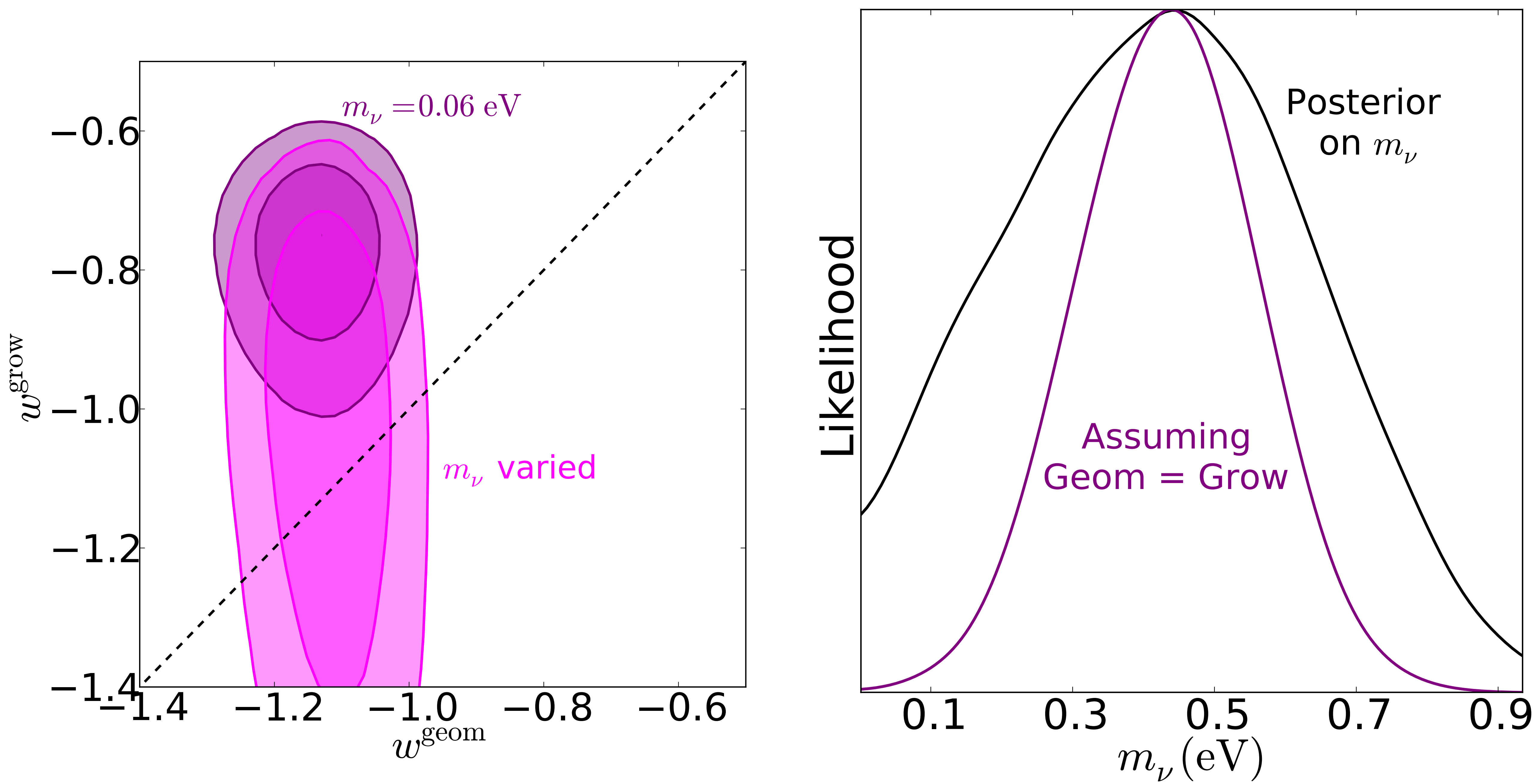
- **Growth of structure** gives an extremely powerful set of measurements to complement geometrical measures
- **Systematics** are challenging but entirely possible to overcome: require sophisticated statistical techniques. Principal challenge: photometric **calibration errors**.
- Separating **growth from geometry** is a good way to get a) constraints b) insights into DE constraints; it now indicates a **3-sigma growth ≠ geometry** discrepancy

EXTRA SLIDES

Redshift Space Distortion data



(Pretty high) neutrino mass can relieve the tension



Ruiz & Huterer, arXiv:1410.5832